ANL/NSE-C2018-18176

Qualification of System-Level Advanced Reactor Safety Analysis Software for Lead Systems

Final CRADA Report

Nuclear Science and Engineering Division

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Qualificaiton of System-Level Advanced Reactor Safety Analysis Software for Lead Systems

Final CRADA Report

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Non Proprietary

Final CRADA Report

For the Office of Scientific and Technical Information (OSTI)

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Participant(s)

Participant 1 name: Westinghouse Electric Company, LLC
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Participant 2 name:
Complete address:

Participant 3 name:
Complete address:

Argonne National Laboratory

Argonne PI(s): Daniel J. O'Grady

Funding Table

To add rows, right-click in bottom row and select "Insert" "rows above".

	Planned Funding	Actual Funding	In-Kind
Government	250,000$	250,000$	
Westinghouse Electric Company, LLC	250,000$	10,000$	240,000$
	$	$	$
	$	$	$
Total	**500,000$**	**260,000$**	**240,000$**

Nature of Work

Describe the research (summary of Scope of Work and principal objectives of the CRADA):

SAS4A/SASSYS-1 [1] is a simulation tool used to perform deterministic analysis of anticipated events as well as design basis and beyond design basis accidents for advanced liquid-metal-cooled nuclear reactors. With its origin as SAS1A in the late 1960s, the SAS series of codes has been under continuous use and development for over forty-five years and represents a critical investment in safety analysis capabilities for the U.S. Department of Energy. Although SAS4A/SASSYS-1 was developed to support the analysis of any liquid-metal-cooled nuclear reactor, it has primarily been utilized to design and analyze Sodium Fast Reactors (SFRs). As a result, most of the qualification basis for SAS4A/SASSYS-1 has utilized sodium as a coolant and geometry descriptions that are prototypic of SFR configurations [2]. In this project, which partnered with Westinghouse Electric Company, LLC, the initial foundation for a qualification basis centered on prototypic pool-type lead-cooled systems has been established, where the end goal is to extend support for utilization of SAS4A/SASSYS-1 in Lead Fast Reactor (LFR) licensing or authorization. This project included three fundamental technical tasks: LFR V&V test suite development (Task 1); qualification support for LFRs (Task 2); and LFR modeling capabilities evaluation and improvement (Task 3).

DOE mission area(s):

Energy and Environmental Science and Technology

Choose an item.

Choose an item.

Conclusions drawn from this CRADA; include any major accomplishments:

V&V Test Suite Development

As part of Task 1, new V&V problems were developed to extend the applicability of the SAS4A/SASSYS-1 V&V basis into LFR design space. In the following subsections a summary of [3], which describes updates to the verification test suite, and [4], which describes updates to the validation test suite, are provided.

Extension of the Verification Test Suite

The SAS4A/SASSYS-1 V&V Test Suite currently contains over 300 test cases. These tests incorporate verification, validation and training input models for various components and system configuration. Reference [2] provides an overview of the verification and validation cases available, while [5] describes in further detail the validation effort for the SAS4A/SASSYS-1 RVACS component model. Verification test cases are developed using the methodology presented in [2]. Analytic solutions have been derived in [6-11] and comparisons have been made between the SAS4A/SASSYS-1 predictions and the analytical solutions in [6-11]. The majority of the verification cases, which are summarized in Table 2-1 in Reference [3], utilize sodium as the reactor coolant and are based on facility layouts that are characteristic of an SFR. At a more granular level, many of the verification test cases can be considered coolant agnostic. These test cases include:

- Cases 1.2 - Case 1.9, which verify that SAS4A/SASSYS-1 correctly captures additional complexity that can be built on top of a base model.
- Case 2.1 - Case 2.4, which verify that the transient solver routines correctly predict the base model response to a zero transient, or simple change in the boundary conditions.
- Case 4.1 - Case 4.22, which verify the core power models.
- Case 5.17, Case 5.18, and Case 5.23 – Case 5.26, which verify that SAS4A/SASSYS-1 correctly captures heat transfer between components.
- Case 6.1 – Case 6.4, which verify the control system logic and its ability to read measured signals.

In order to extend the coverage of the SAS4A/SASSYS-1 verification test suite into LFR design space, several of the SFR specific test cases have been recreated for lead as a coolant and facility layouts that are more representative of an LFR. In order to reduce the number of new test cases, the SFR specific test cases were further analyzed to identify overlapping characteristics. As a result of this analysis, seven new test cases were created for LFR. These test cases are summarized in Table 1. Case 1.10 is a recreation of Case 1.1 using channel dimensions that are representative of an LFR to provide a base case for LFR testing. Cases 3.8 – 3.11 are recreations of Cases 3.1 – 3.6, respectively, confirming that the built-in lead coolant thermophysical properties are utilized correctly. Cases 5.1, 5.16, and 5.27 have been recreated and combined as Case 5.28 in order to demonstrate that SAS4A/SASSYS-1 correctly distributes the steady state coolant temperatures, and transitions to a new equilibrium temperature distribution using a primary heat exchanger for an LFR facility layout. Cases 5.7 – 5.12 and Cases 5.19 – 5.21 have been recreated and combined as Case 5.29 in order to demonstrate that SAS4A/SASSYS-1 correctly distributes and maintains the pressure throughout the primary system for an LFR facility layout. Collectively, these test cases capture all of the SFR specific verification testing that has been performed and extend the coverage into LFR design space.

Table 1 Overview of new SAS4A/SASSYS-1 LFR-based Verification Test Cases

Case	Description	Outcome
	Simple Steady State Cases	
1.10	Base LFR Fuel Channel	Acceptable
	Material Property Cases	
3.8	LFR Temperature-Dependent Coolant Density	Acceptable
3.9	LFR Temperature-Dependent Coolant Heat Capacity	Acceptable
3.10	LFR Temperature-Dependent Coolant Thermal Conductivity	Acceptable
3.11	Temperature-Dependent Built-In Lead Properties	Acceptable
	Heat Removal System Cases	
5.28	LFR Equilibrium Temperature Distribution	Acceptable
5.29	LFR Equilibrium Pressure Distribution	Acceptable

In order for a test case to be considered acceptable there must be agreement between the SAS4A/SASSYS-1 results and the analytical solution for the temperature and pressure within the respective component. For case 1.10 and Case 3.8 – Case 3.11, the core channel is the component of interest. Comparisons were made for the following Quantities of Interest (QOI):

- Fuel centerline temperature,
- Fuel surface temperature,
- Cladding inner surface temperature,
- Cladding outer surface temperature,
- Coolant temperature, and
- Axial pressure distribution with the coolant channel.

In Case 5.28 and 5.29, the primary heat transport system is the component of interest. Case 5.28 focuses on the temperature distribution within the primary heat transport system. Comparisons were made for the following QOI:

- Temperature between the inlet of the primary heat exchanger and the core outlet,

- Temperature between the outlet of the primary heat exchanger and core inlet,
- Temperature profile within the primary heat exchanger.

In Case 5.29, the pressure distribution within the primary heat transport system was verified. Comparisons were made for the following QOI:

- Pressure drops in segments two through four,
- Pressure in the compressible volumes,
- Steady state Liquid/Gas interface elevation,
- And Pump Head.

All temperature QOIs were found to be within 0.1 K of the analytic solution and all pressure QOIs were found to be within 0.1 kPa. These values were selected based on the minimum precision of the standard output.

Additional work is required to close remaining gaps in the verification testing of SAS4A/SASSYS-1. Future efforts will focus on developing verification tests that are reactor-type agnostic such that the test suite coverage is extended for both SFRs and LFRs. In combination with the ongoing validation efforts, the comprehensive SAS4A/SASSYS-1 verification test suite summarized in this report demonstrates the applicability of SAS4A/SASSYS-1 for LFR design and licensing activities.

Extension of the Validation Test Suite

Similar to the verification test suite, an extensive review was performed of the SAS4A/SASSYS-1 validation test suite. Scaling analysis performed for Separate Effect Tests (SETs) and Integral Effect Tests (IETs) prevents tests from being system agnostic, requiring the creation of new LFR specific validation test cases. A survey of existing lead and LBE test facilities was performed to support the development of an LFR validation database for SAS4A/SASSYS-1. A review of the 72 Pb/LBE test facilities contained within the IAEA database determined that many of the tests were not suitable for the validation of SAS4A/SASSYS-1. A total of six SET facilities and three IET facilities were determined to be suitable:

- Separate Effects Tests
  - NACIE-UP facility
  - TALL-3D facility
  - LIFUS 5 facility
  - HELENA facility
  - KYLIN-II facility
  - SPRUT facility
- Integral Effects Test
  - CIRCE facility
  - E-SCAPE facility
  - CLEAR-S facility

In order to gain access to comprehensive experimental data, not available within public literature, a collaboration with ENEA was established. ENEA maintains and operates three of the SET, NACIE-UP, LIFUS 5 and HELENA, and one of the IETs, CIRCE. At the suggestion of ENEA, a protected loss of flow experiment conducted at CIRCE was selected for assessing the ability of SAS4A/SASSYS-1 to model natural circulation.

CIRCE-HERO is part of a larger experimental research and development program funded by the European Commission (EC EURATOM-H2020) in the frame of the SESAME project, coordinated by ENEA The facility is divided into two distinct sections, CIRCE, a large cylindrical vessel, and HERO, a bayonet tube heat exchanger. CIRCE has hosted a number of different experiments including Protected Loss of Flow (PLOF) and Protected Loss of Heat sink (PLOH) accidents scenarios using both the ICE and HERO heat exchanger components. The primary working fluid is lead-bismuth eutectic (LBE) and the secondary working fluid in HERO is water/steam. For the CIRCE-HERO experiments the Fuel Pin Simulator (FPS), fitting volume and riser were maintained from the CIRCE-ICE experimental layout. Additional details on the CIRCE-HERO facility can be found in [12, 13]. The SAS4A/SASSYS-1 representation of the CIRCE-HERO layout is shown in Figure 1.

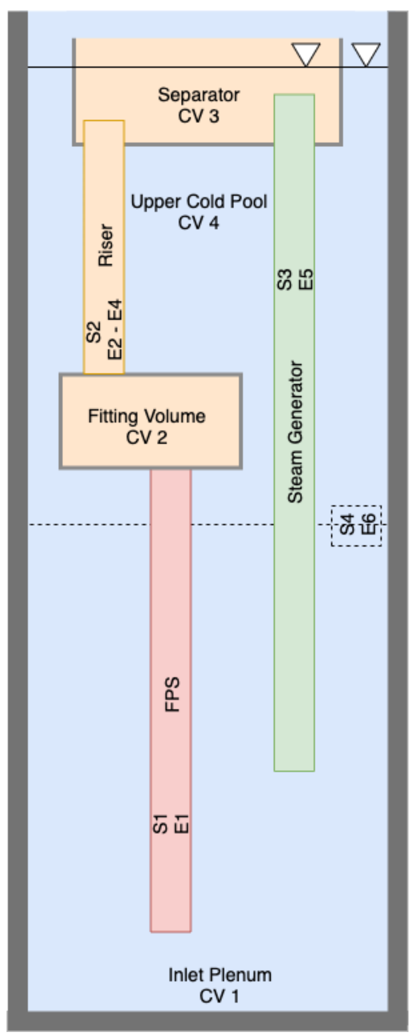

Figure 1 SAS4A/SASSYS-1 Component Layout for the CIRCE-HERO Facility

SE-Test3 was selected to be used as a validation case for SAS4A/SASSYS-1. SE-Test3 is one iteration in a series of PLOF accident scenarios. In SE-Test3, the pump head, which is provided by argon gas injection, is assumed to follow a cost down curve, where the pump head is zero MPa after 300 seconds. The FPS power follows a prototypic decay heat curve, with a rapid decrease in power to approximately 20 % of the operating power followed by a slow decay to a final power of 20 kW. A number of approximations were required to model SE-Test3 using SAS4A/SASSYS-1. The approximations, which include simplifications to the gas injection and steam generator, are described in [4].

Figure 2 contains a comparison between the SAS4A/SASSYS-1 predicted flow rate and the measured LBE flow rate at the FPS inlet. In the early stages of the transient, when gas is being injected below a flow rate of 1 Nl/s, the SAS predictions are significantly different from the measured values. This result is expected due to the simplifications made to the SAS pump head and the complex behavior of two-phase flow within the riser and separator. After the gas injection has stopped, 300 s +, the SAS predicted mass flow rate agrees well with the measured value. An increasing trend is observed in the SAS predictions that is not evident in the measured values. This discrepancy is believed to be caused by differences in the LBE pool temperatures, which influence the buoyancy head within the system.

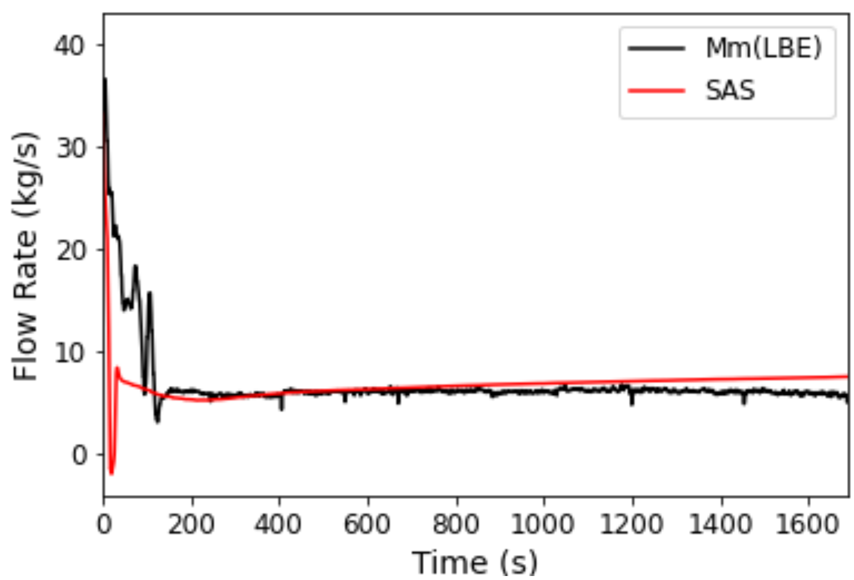

Figure 2 SAS4A/SASSYS-1 LBE Mass Flow Rate Predictions.

Additional comparisons are made between core inlet temperature, core outlet temperature, HERO inlet temperature, the upper cold pool temperature, and the lower cold pool temperature. Approximations to the component heat transfer and thermal stratification modeling introduced minor errors to the core inlet and core outlet temperature predictions. In general, the SAS4A/SASSYS-1 predictions agree well with the experimental measurements for SE-Test3. Further study is required to improve the boundary conditions on the FPS outer wall. Future work will focus on explicitly modeling the steam generator within the SAS4A/SASSYS-1 BOP module.

Additionally, a coupled SAS4A/SASSYS-1 CFD model will be developed to improve the predictions of the upper and lower cold pool temperatures.

Qualification Support

In the absence of a 10 CFR Part 50, Appendix B-approved QA program, a commercial license applicant will need to pursue closure of non-compliance by means of 10 CFR Part 21, where the software qualification, or commercial-grade dedication (CGD), process is typically utilized. The CGD (qualification) process provides reasonable assurance that a commercial-grade item will perform its intended safety function and comply with specified requirements. This project utilized high-level best practices identified in EPRI Technical Report 1025243, “Plant Engineering: Guideline for the Acceptance of Commercial-Grade Design and Analysis of Computer Programs Used in Nuclear Safety-Related Applications” [14] for the CGD process to build an initial foundation of qualification support for the application of SAS4A/SASSYS-1 to LFR systems. Key aspects of EPRI TR 1025243 utilized in this project include:

- Identification of critical characteristics (CC);
- Establishment of acceptance criteria for each critical characteristic;
- Identification of acceptance methods for each critical characteristic; and
- Documentation of technical evaluation and results.

To this end, acceptance Method 1, which uses special tests and inspections, is the primary acceptance method used in this project. Acceptance Method 3, source verification, is also utilized to support critical characteristic acceptance throughout Task 3 on modeling enhancements, although most new SAS4A/SASSYS-1 development verification activities are test-driven.

Because the remainder of this report documents the technical details associated with each task, only high-level descriptions of the mechanisms supporting CGD are provided here. Table 2 below provides an overview of how a subset of EPRI TR 10025243 elements were utilized in this project. Given the scope and timeline of this project, a full expansion of CC identification was not completed, but instead a limited set of known CCs and phenomena were prioritized by the project partner and included in this project. Prioritized V&V and modeling improvement activities were guided by an existing PIRT exercise which was completed independently by Westinghouse.

Table 2 Overview of qualification activities

EPRI TR 1005243 element	Task 1 application	Task 3 application
CC identification	Existing verification test suite considered to be a preliminary evaluation of fundamental CCs. Existing cases were reviewed for applicability to lead coolant. New test cases were developed for cases which were not coolant agnostic. With respect to validation, given results of a previously-completed PIRT exercise, important phenomena were identified at a high level, including natural circulation.	Given output of PIRT exercise, modeling and simulation capabilities necessary to model important phenomena were identified.
Acceptance criteria	Acceptance criteria inherently defined within test problem description.	Acceptance criteria defined within a software requirements specification document.
Acceptance methods	Special testing. For verification, new test cases were developed which were specific to lead coolant. For validation, data sources (CIRCE-HERO) were identified and new test problems were developed.	Special testing and source verification.
Documentation	Description of input/output, figures of merit, acceptance criteria, and acceptance results.	Description of input/output, figures of merit, acceptance criteria, and acceptance results.

Modeling Capability Enhancements

Two of the components that were identified during PIRT development as having high importance were the Primary Heat eXchanger (PHX) and the Passive Heat Removal System (PHRS). Each component plays a critical role in the heat transport system during normal and off-normal operation. The PHX thermally couples the lead coolant to the power conversion system. The PHRS provides emergency core cooling during off-normal operation. In order to support the assessment LFRs that utilizes PHXs and a PHRSs, new SAS4A/SASSYS-1 developments were pursued.

Development of a Primary Heat Exchanger (PHX) Component

SAS4A/SASSYS-1 V5.3 contained three options for modeling heat exchangers, a table heat exchanger, a detailed Intermediate Heat eXchanger (IHX), and a detailed Steam Generator (SG). Each modeling option comes with its own requirements: the table heat exchangers require the user to predetermine the response of the primary coolant following a transient; The detailed IHX requires the user to create a complete intermediate loop; and the detailed SG requires the user to develop a balance of plant model. While the table heat exchanger provides users with an option for omitting an intermediate or balance of plant loop, the thermal coupling between the primary coolant and the power conversion system cannot be adequately captured using prescribed boundary conditions on the primary coolant. In order to capture the thermal coupling between the primary and power conversion system, while removing the need for a detailed secondary loop, the detailed PHX option was developed.

The detailed PHX option was developed as an extension of the detailed IHX. Both the detailed PHX and the IHX options use a shell and tube geometry shown in Figure 3. Users have the flexibility to define the primary side as the shell-side or the tube-side within the heat exchanger. In the case of helical-coil heat exchanger, the user can use a slant factor to capture the increased heat transfer area between the tube and the shell. The only difference between the detailed IHX and the PHX option is the definition of a secondary loop. Instead of defining a secondary loop, the detailed PHX options requires user to specify a coolant mass flow rate and a coolant temperature at the inlet of the secondary side.

In addition to the development of a PHX option, the detailed heat exchanger routines were updated to allow for greater flexibility in the modeling of heat transfer coefficients. The functional form of the heat transfer coefficient was updated to allow for correlations that differ from liquid metal correlations. The new functional form,

$$Nu = C_1(Re^{C_2}Pr^{C_2+C_4}) + C_3 \tag{1}$$

allows users to specify heat transfer coefficients as a function of the Reynold Number (Re) and the Prandtl Number (Pr), which is required for more advanced heat exchanger fluids, such as super-critical CO_2. In the case that a user does not specify a fourth coefficient, C_4 the heat transfer coefficient becomes a function of the Peclet Number (Pe = RePr), which is typical for liquid metal coolants.

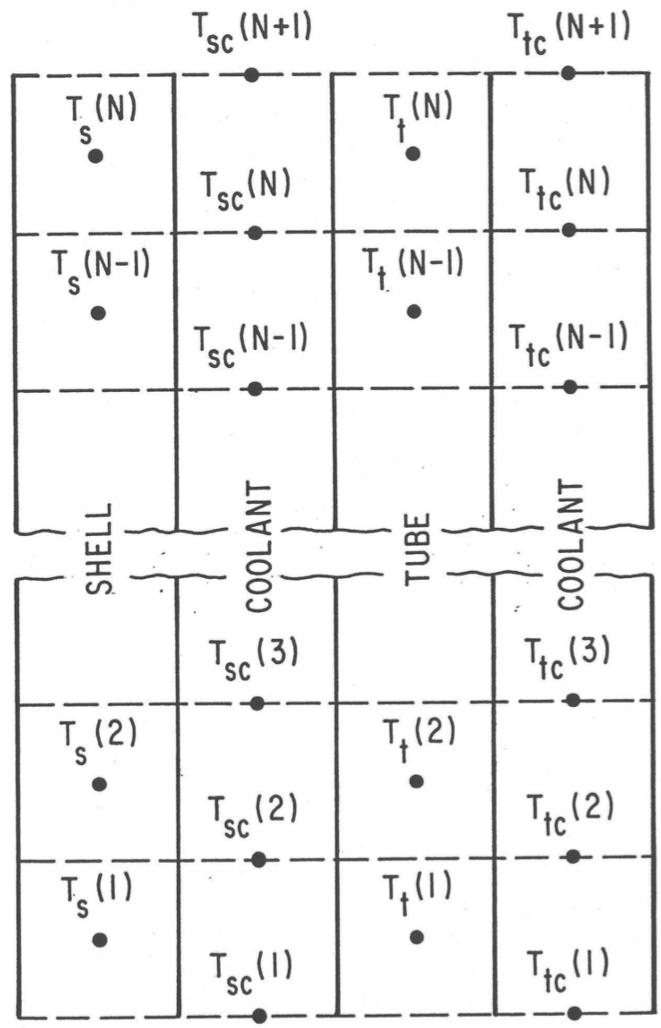

Figure 3 Shell and Tube Heat Exchanger Schematic.

Development of a Coupled Reactor Vessel Auxiliary Cooling System (RVACS) Component

The objective of the PHRS is to remove heat from the primary system through the reactor vessel. SAS4A/SASSYS-1 V5.3 contained two options to account for the effects of a heat transfer through the reactor vessel: a simple table lookup option and a semi-customizable representation of an RVACS. Both options rely on a connection to components within the SAS4A/SASSYS-1 primary heat transport system model. To account for heat removal at the reactor vessel wall, SAS4A/SASSYS-1 utilizes a component to component heat transfer framework. This framework utilizes Newton's law of cooling to allow for heat transfer between any two components, A and B:

$$Q_{snk} = h_{snk} A_{snk} (T - T_{snk}) \tag{2}$$

where Q_{snk} is the amount of heat being transferred to/from component A, A_{snk} is the heat transfer area between components A and B, h_{snk} is the Heat Transfer Coefficient (HTC), T_{snk} is the temperature of component B, and T is the temperature of component A. Within a timestep, SAS4A/SYS-1 assumes that h_{snk} and T_{snk} remain constant. This allows components A and B to be coupled loosely and avoids the need to solve a matrix for all components at each time step. Utilizing this framework, component B is representative of the system beyond the RV, i.e., PHRS or RVACS, whereas the reactor vessel wall is representative of component A. The reactor vessel wall may be described using more than one built-in SAS component, where all components comprising the reactor vessel wall are stacked axially and can be assigned as a combination of compressible volume and pipe walls. When the simple table model is selected, SAS4A/SASSYS-1 applies a user-defined, temperature-dependent h_{snk} to reactor vessel wall. Alternatively, the detailed RVACS model invokes the implementation solution for a conventional air-cooled RVACS configuration.

Detailed RVACS Model

In the detailed RVACS model, the heat transfer within the structures surrounding the reactor vessel is determined using a representative RVACS geometry. This geometry, shown in Figure 4, contains a guard vessel, an air riser, an outer shell, an air downcomer, an outer wall, and a constant temperature sink. The temperature of the guard vessel and the heat transfer coefficient between the guard vessel and the reactor vessel are used by SAS4A/SASSYS-1 as h_{snk} and T_{snk} to update the reactor vessel temperature according to Eq. 2. In the example configuration shown in Figure 4, the reactor vessel is comprised of two compressible volumes, Pool 3 and Pool 4. The width, surface area, and material properties of each structure following the reactor vessel are provided by the user. Radiative and convective heat transfer are captured between each of the structures in the geometry, and the mass flow rate of the air is determined by balancing the buoyancy pressure head with the frictional pressure losses.

Ongoing validation efforts have shown good agreement between the SAS4A/SASSYS-1 detailed RVACS predictions and a set of 1980s Natural Convection Shutdown Heat Removal Test Facility (NSTF) experimental data [15, 16]. However, the detailed RVACS model does not provide users the flexibility to simulate RVACS geometries that vary from the standardized configuration prevalent in most pool-type liquid metal-cooled reactor designs. For example, the PHRS, which relies on the evaporation of water and subsequent natural convection of air, cannot be accurately modeled using the detailed RVACS model [17]. For this reason, a new coupled RVACS model was developed to allow users increased flexibility when modeling the heat transfer contributions of an RVACS.

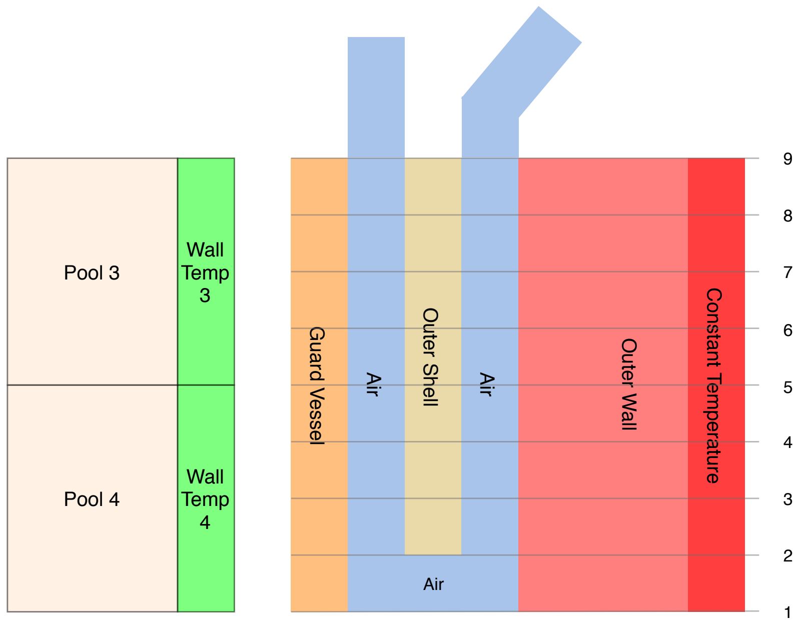

Figure 4 SAS4A/SASSYS-1 Detailed RVACS Geometry

Coupled RVACS Model

In the coupled model, the outer edge of the reactor vessel wall represents the surface at which, beyond this boundary, all phenomena are treated by an external calculational tool. At the end of each timestep, SAS4A/SASSYS-1 transfers the temperature of each axial node in the vessel wall to an external code. The external code is expected to provide a sink temperature and heat transfer coefficient for each node. Using these values, SAS4A/SASSYS-1 will update the vessel wall temperature using Eq. 2. A graphical representation of the coupled model is shown in Figure 5. When compared to Figure 4, the new coupled model treats the RVACS heat transfer as a black box. The coupled model relies on ZMQ for data transfer between SAS4A/SASSYS-1 and the external code. ZMQ is a C++ asynchronous messaging library that allows for data transfer interfaces that are simple to create and flexible [18].

One external code that has been successfully coupled with SAS4A/SASSYS-1 is the containment analysis software GOTHIC [19]. GOTHIC has the ability to model two-phase flow, including the evaporation of water. Using this modeling capability, the behavior of a PHRS, both the evaporation stage and the air natural circulation stage, can be captured with sufficient accuracy. In order to allow for the communication between SAS4A/SASSYS-1 and GOTHIC an intermediate coupling software was created to translate between ZMQ and named pipes, which is the methodology GOTHIC uses to exchange data with external software. In addition to translating, the intermediate coupling software, Sas2Goth, controls the time step synchronization between SAS4A/SASSYS-1 and GOTHIC and creates a detailed log file of the information exchanged. This capability has been demonstrated in [17], where the transition from evaporation to air cooling within a PHRS was observed during a coupled SAS4A/SASSYS-1/GOTHIC simulation.

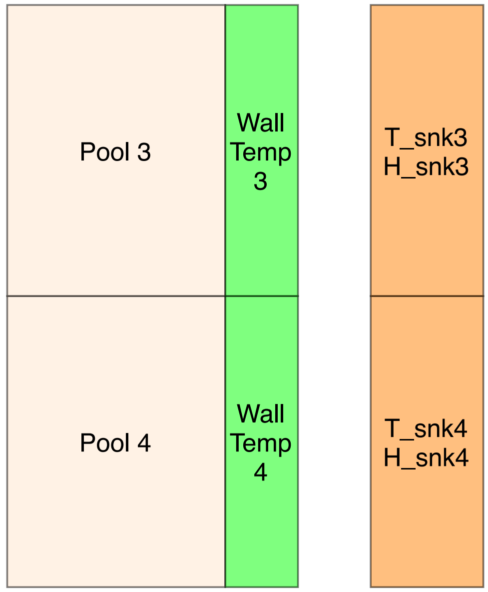

Figure 5 Coupled model geometry.

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Technology Transfer-Intellectual Property

Argonne National Laboratory background IP:

SAS4A/SASSYS-1 Safety Analysis Code System

Participant(s) background IP:

WEC Lead Fast Reactor Phenomena Identification and Ranking Table (PIRT)

Identify any new Subject Inventions as a result of this CRADA:

N/A

Summary of technology transfer benefits to industry and, if applicable, path forward/anticipated next steps towards commercialization:

In collaboration with Westinghouse Electric Company, LLC, the initial foundation for a qualification basis centered on prototypic pool-type lead-cooled systems has been established. Three tasks have been completed to extend support for utilization of SAS4A/SASSYS-1 in LFR licensing or authorization. The key technical outcomes of this project include the following: 1) A V&V test suite for lead systems that includes test problems and related documentation; 2) A documentation framework that supports CGD and qualification of fundamental LFR licensing topics in the transient and accident analysis space and a path forward for SAS4A/SASSYS-1 qualification by vendors; and 3) a reduction in SAS4A/SASSYS-1 LFR modeling capabilities gaps. These technical outcomes have been achieved using prototypic LFR designs, and therefore support general commercialization of the LFR design.

While each of these outcomes contributes in the near-term to the commercial viability of SAS4A/SASSYS-1 as an LFR licensing tool, the predominant goal of this project was a marked reduction in one of the key LFR licensing barriers that is the availability of a pedigreed LFR safety analysis tool. Additional work is required to further increase the commercial viability of SAS4A/SASSYS-1 as an LFR licensing tool. Many of the LFR phenomena and critical characteristics identified in task 2, are multi-physics in nature or require a combination of system level and component level modeling. One example of a multi-physics-based analysis that is important in a modern regulatory framework is Mechanistic Source Term (MST) analysis, which tracks the transport of isotope following fuel failure. One common way to perform MST analysis is to use the predictions of a safety analysis calculation to inform a string of calculations capturing the isotopic transport from a fuel pin to containment. As part of task 2, the SAS4A/SASSYS-1 user interface was found to lack the flexibility necessary for efficient multi-physics analysis. Using the experience gained in task 3 of this project, WEC and the SAS4A/SASSYS-1 development team will continue to seek opportunities to work together in identifying and closing modeling deficiencies within SAS4A/SASSYS-1 and further extending the V&V test suite to support and enable the long-term goal of LFR commercialization.

Other information/results (papers, inventions, software, etc.):

Paper/Reports

1. D. O’Grady *et al.*, "SAS4A/SASSYS-1 Lead Verification Test Suite," Argonne National Laboratory, Lemont, IL, ANL/NSE-21/25, 2021.
2. D. O’Grady *et al.*, "Assessment of SAS4A/SASYS-1 Against CIRCE-HERO Loss of Flow Test," presented at the The 19th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-19), Brussels, Belgium, March 6-11, 2022 (Submitted).
3. J. Liao *et al.*, "Joint SAS4A/SASSYS-1 Development for Lead Cooled Fast Reactor Safety Analysis," presented at the 2020 American Nuclear Society Virtual Winter Meeting Chicago, IL, November 16 - 21, 2020.
4. D. O’Grady *et al.*, "Implementaion of an Extended Reactor Vessel Heat Rejection Modleing Capability in SAS4A/SASSYS-1," presented at the 2020 American Nuclear Society Virtual Winter Meeting Chicago, IL, November 16 - 21, 2020.

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